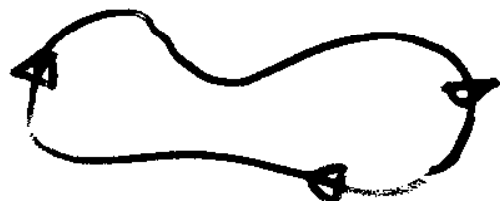


MAGIC, MYSTERY, AND MATRIX ⁽¹⁾

AT LEAST IN HINDSIGHT,
STRING THEORY BEGINS WITH
THE NAIVE IDEA THAT
ELEMENTARY PARTICLES

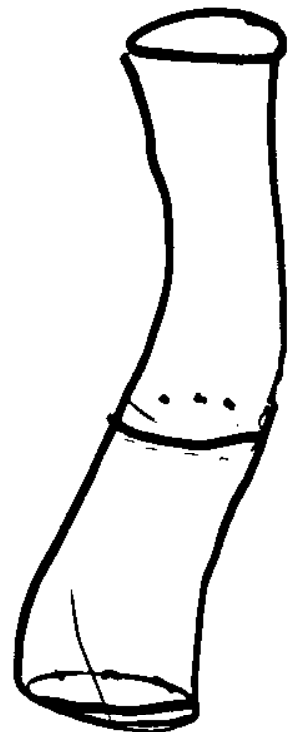
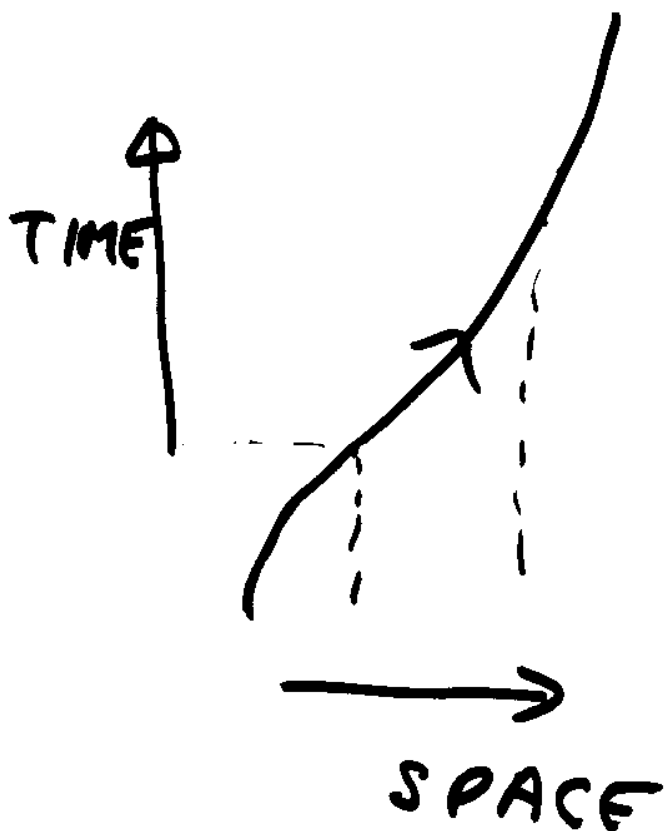
- PHOTONS, QUARKS, NEUTRINOS,
ETC. — ARE NOT

(QUANTUM) POINT PARTICLES
BUT STATES OF A VIBRATING
STRING



DIFFERENT PARTICLES ARE ^②
DIFFERENT HARMONICS OF ONE
STRING ... AND THUS UNIFICATION
IS ACHIEVED.

SPACETIME
PICTURE



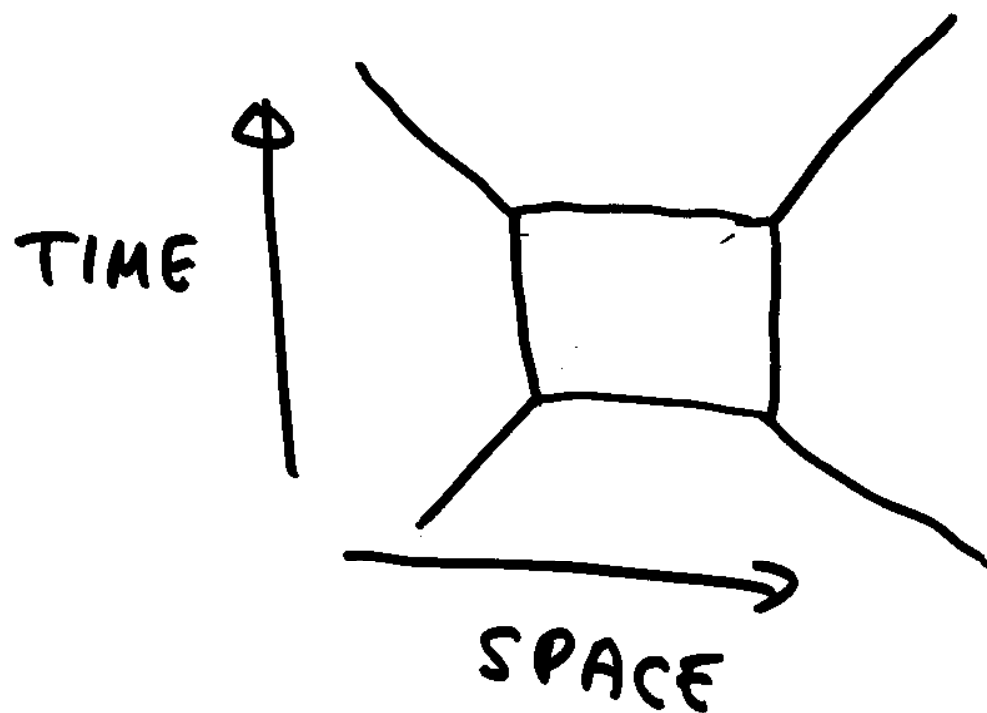
③

IT SURELY IS SURPRISING
THAT THIS NAIVE-SOUNDING IDEA
LEADS TO A DEFINITE AND
FAR-REACHING THEORY....

PERHAPS THE SIMPLEST
EXPLANATION OF THAT
COMES BY CONTEMPLATING
THE "FEYNMAN DIAGRAMS"
THAT DESCRIBE PARTICLE
INTERACTIONS

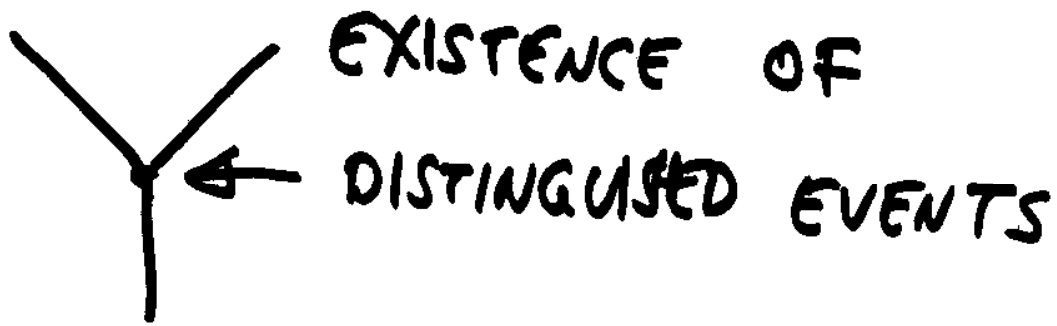
④

FEYNMAN DESCRIBED INTERACTIONS
VIA "FEYNMAN DIAGRAMS"



PARTICLES BRANCH AND JOIN
IN SPACE TIME. A POWERFUL
IDEA, BUT ALSO EXHIBITS THE
LIMITATIONS OF
QUANTUM FIELD THEORY

⑤



LEADS TO

* INFINITIES

AT $x=y$

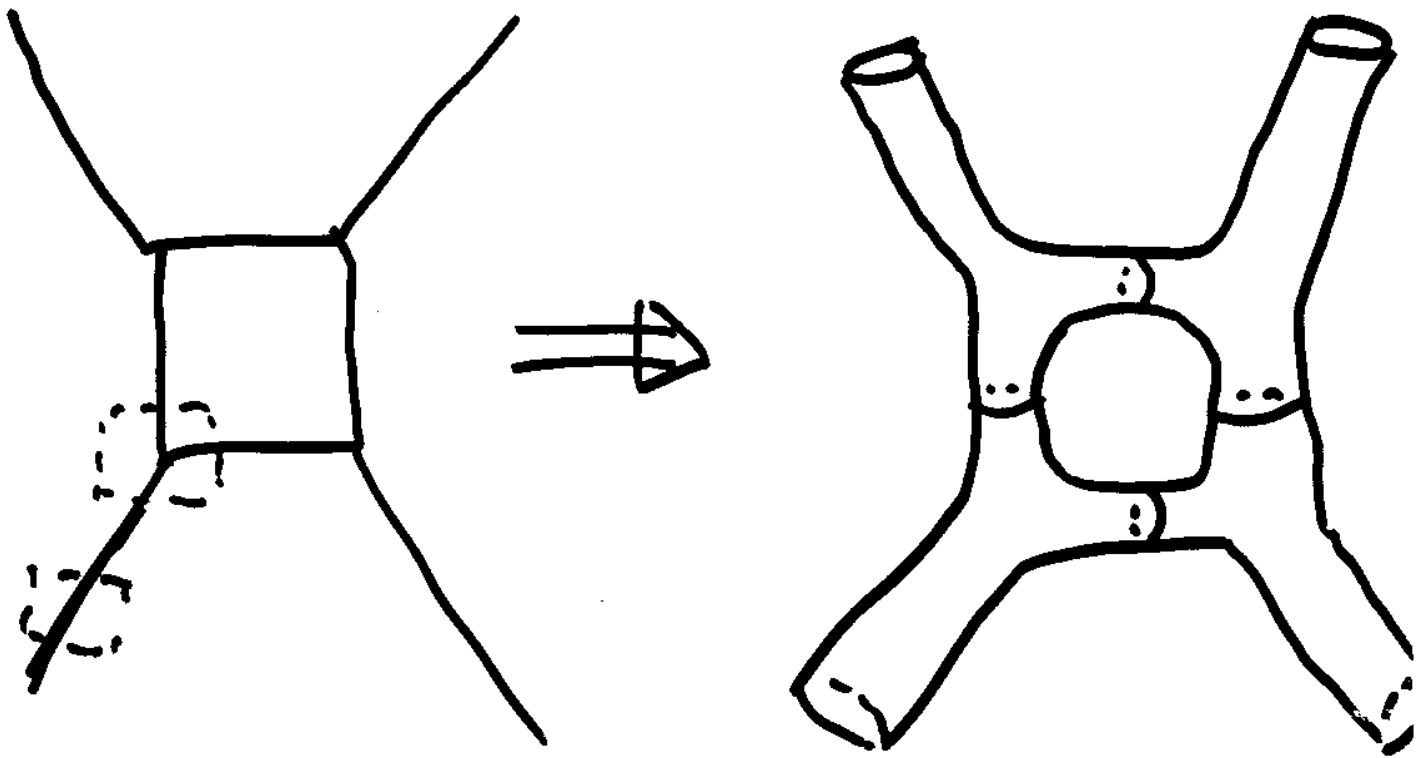


* * LIMITATIONS OF
PREDICTIVE POWER : TOO
MANY THEORIES....

* * * DEFINITE ROLE OF
SPACE-TIME POINTS

IN STRING THEORY

⑥

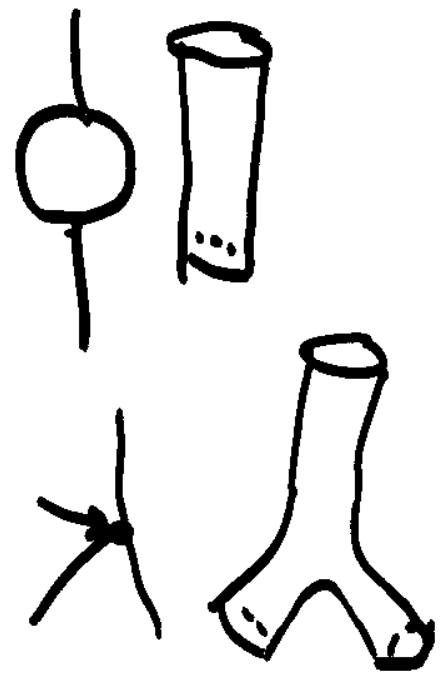


THE TWO PICTURES LOOK SIMILAR
IF VIEWED FROM A BIG DISTANCE,
BUT IN THE STRING CASE
THERE ARE NO DISTINGUISHED
EVENTS, ANY SMALL PIECE
LOOKS LIKE ANY OTHER....

(7)

AS A RESULT ...

* NO INFINITIES IN
STRING THEORY



* * MUCH FEWER THEORIES
AND MORE PREDICTIVE
POWER

* * * THE CONCEPTS
OF SPACETIME
CHANGE COMPLETELY

CONCERNING THE PREDICTIVE ⁽⁸⁾
POWER, IN THE SAME
SENSE THAT QUANTUM FIELD
THEORY MAKES A GENERAL
PREDICTION - ANTIMATTER - THAT
DOESN'T DEPEND ON CHOICE OF
A PARTICULAR MODEL

STRING THEORY MAKE THREE
GENERAL PREDICTIONS THAT
DON'T DEPEND ON UNDERSTANDING
THE QUANTUM GROUND STATE

THEY ARE

(9)

* GRAVITY, I.E. GENERAL
RELATIVITY WITH SMALL
CORRECTIONS

** NON ABELIAN GAUGE SYMMETRY
= BREAD AND BUTTER OF THE
STANDARD MODEL

*** SUPERSYMMETRY
(= INCORPORATION OF QUANTUM
VARIABLES IN SPACETIME)
PRIME TARGET FOR ACCELERATORS

9.5

AND UNIFIED MODELS
OF GRAVITY PLUS
PARTICLE PHYSICS THAT
ARE STRIKINGLY ELEGANT
AND BEAUTIFUL....

(10)

AS FOR THE NUMBER OF
THEORIES, AS TRADITIONALLY
UNDERSTOOD (ca. 1985) THERE
ARE 5 STRING THEORIES

(Type I, heterotic $E_8 \times E_8$ and $SO(32)$,
Type IIA, Type IIB)

A BIG IMPROVEMENT OVER THE
STANDARD SITUATION

(INFINITELY MANY QUANTUM
FIELD THEORIES)

BUT STILL FOUR TOO MANY.

THE FIVE THEORIES WERE
DISCOVERED FROM 1977 - 1984

(11)

~~ROUGH~~

MOST THEORIES WE STUDY
IN PHYSICS HAVE ONE OR
MORE • DIMENSIONLESS PARAMETERS
THAT CAN BE VARIED,
FOR INSTANCE

$$\alpha = \frac{e^2}{4\pi} \approx \frac{1}{137}$$

IN THE CASE OF QED.

THE FIVE STRING THEORIES
HAVE THE PROPERTY THAT THE
EQUATIONS THEMSELVES ARE
UNIQUE, AND CONTAIN NO
VARIABLES.

THIS IS ATTRACTIVE... BUT ⁽¹²⁾
ENSURES THE THEORIES WILL BE
HARD TO UNDERSTAND.

WHILE THE EQUATIONS ARE
UNIQUE, THE SOLUTIONS ARE NOT
... A FIELD ϕ (THE "DILATON")
CAN HAVE (CLASSICALLY) AN
ARBITRARY VACUUM EXPECTATION
VALUE, AND THERE IS
AN EFFECTIVE COUPLING

$$g_{eff} = e^{\phi}$$

TRADITIONALLY WE ONLY
UNDERSTAND STRING

(13)
 $g_{\text{eff}} = e^{\phi}$

THEORY WHEN $g_{\text{eff}} \ll 1$.

AS IN OTHER AREAS OF
PHYSICS, SUCH A RESTRICTION
CAN CONCEAL ALL KINDS OF
THINGS.....

(15)

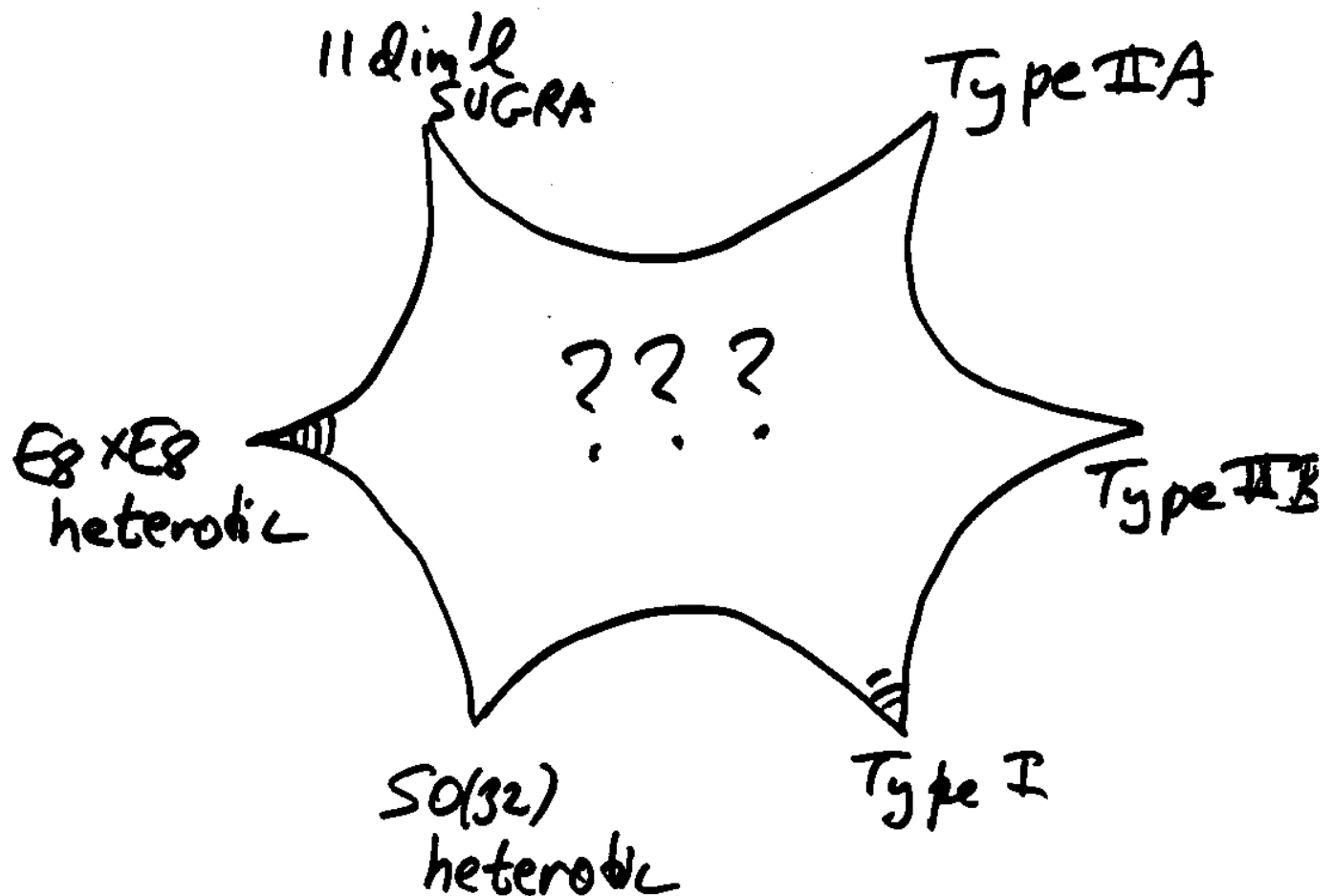
IT TURNS OUT THAT

TWO OF THESE QUESTIONS ARE
LINKED:

* IF ONE OF THE FIVE
STRING THEORIES IS RIGHT,
WHO LIVES IN THE OTHER
FOUR WORLDS?

* * WHAT HAPPENS IF
 $g_s \gg 1$?

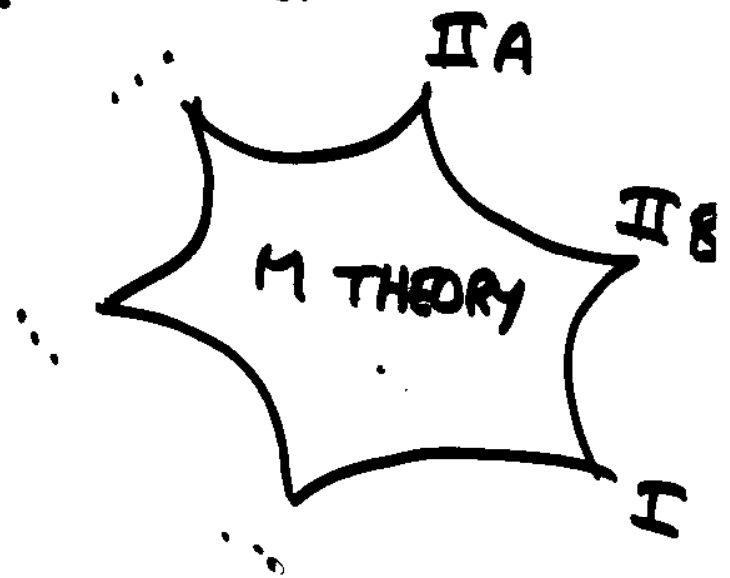
AS IT HAS TURNED OUT, (16)
THE FIVE TRADITIONALLY KNOWN
STRING THEORIES ARE DIFFERENT
LIMITING CASES OF ONE THEORY



THE THEORY IN THE
CENTER - OFTEN CALLED
M-THEORY WHERE M STANDS
FOR MAGIC, MYSTERY, OR MATRIX
- IS THUS, THOUGH
STILL SCARCELY UNDERSTOOD,
THE CANDIDATE FOR
SUPERUNIFICATION OF THE
LAWS OF NATURE.

(18)

HOW DOES ONE BUILD
UP THIS
PICTURE?



AN OVERSIMPLIFIED VERSION
IS AS FOLLOWS :

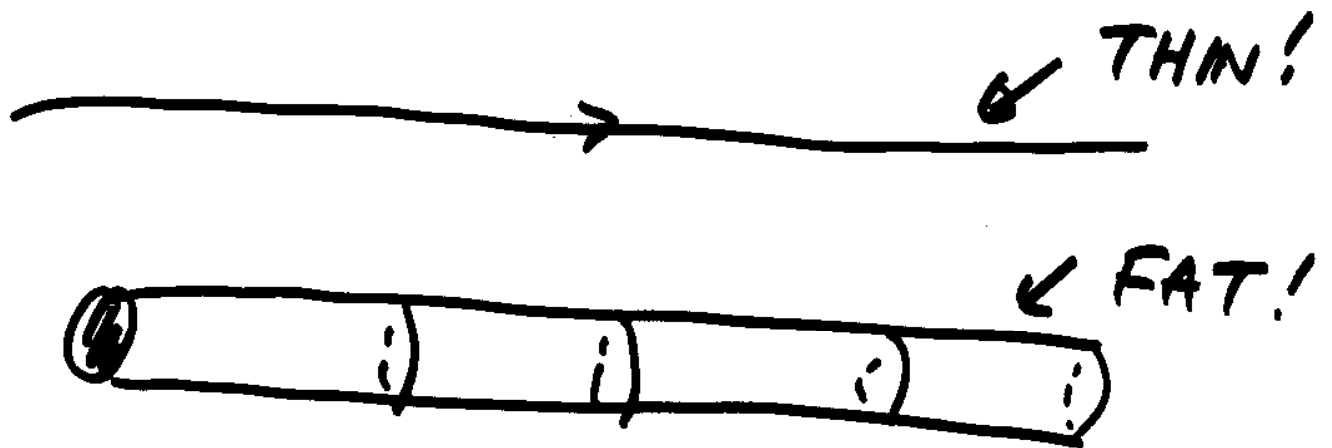
ONE STUDIES ONE OF THE
STRING THEORIES, SAY TYPE I
IN ADDITION TO "ELEMENTARY
STRINGS". IT CONTAINS

19

YOU LOOK MORE CLOSELY,

"COLLECTIVE EXCITATIONS"

OR "SOLITONIC STRINGS"



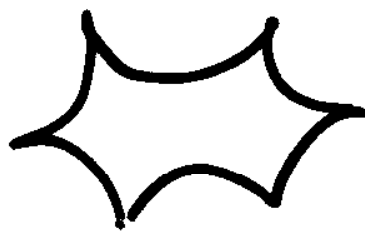
WHEN g_{eff} BECOMES LARGE
THE "FAT" STRINGS BEHAVE
AS ELEMENTARY STRINGS OF
A DIFFERENT STRING THEORY...

THIS IS AN OLD STRATEGY
IN, SAY, TWO-DIMENSIONAL
MATHEMATICAL PHYSICS ;

IT TURNS OUT THAT IT
CAN BE IMPLEMENTED VERY
PRECISELY IN THE PRESENCE
OF SUPERSYMMETRY, AND
GIVES PARTICULARLY DRAMATIC
RESULTS IN STRING THEORY....

(21)

BY GOING DOWN THIS ROAD,
ONE HAS BY NOW BUILT UP
A "WEB OF DUALITIES" LINKING
THE 6 TRADITIONAL THEORIES
GOING FAR BEYOND THE
STATEMENT THAT THEY ARE ONE



AND LEADING TO MANY
SURPRISING NEW INSIGHTS....

(22)

IN BUILDING UP THE WEB
IT BECAME CLEAR THAT THERE
ARE REALLY THREE KINDS OF
OBJECTS IN THIS THEORY

POINTLIKE



"ORDINARY"
OBJECTS

MASS ~ 1

?

MASS

$\sim \frac{1}{g_{\text{eff}}}$



SOLITONS

MASS $\sim \frac{1}{g_{\text{eff}}^2}$

AS WELL AS "TYPICAL" ELEMENTARY
QUANTA AND SOLITONS, WITH
MASSES ~ 1 OR $\sim \frac{1}{g^2}$, THERE IS
AN INTERMEDIATE KIND OF OBJECT.

(23)

WHAT ARE THEY?

BOTH THE SOLITONS
AND THE "NEW" OBJECTS
WERE ORIGINALLY DESCRIBED
AS BLACK HOLES, BUT THE
BLACK HOLE DESCRIPTION
ISN'T REALLY VALID.

CLASSICAL BLACK HOLES ARE
ONLY A GOOD APPROXIMATION
IF THE "SCHWARZSCHILD RADIUS"
IS BIG ENOUGH.....

(24)

IN THIS CASE THE CRITERION
IS

$$\text{MASS} \gg \frac{1}{g^2}$$

FOR THE SOLITONS

$$M \sim \frac{1}{g^2} \quad \text{THIS IS}$$

BORDERLINE - NOT TOO BAD
BUT NOT TOO GOOD.

FOR THE OTHER OBJECTS OF

$$\text{MASS} \sim \frac{1}{g}$$

IT IS DEFINITELY WRONG

(25)

THEY ARE "SUB-PLANCKIAN
BLACK HOLES".... AND SOUND

OUT OF REACH ... BUT A

VERY SATISFYING EXPLANATION

OF THEIR STRUCTURE HAS BEEN

GIVEN BY POLCHINSKI.

I 'LL EXPLAIN IT INTUITIVELY

Type II



CLOSED
ONLY

(26)

- . - . - . - . - . - .

BLACK HOLE



- - - - - - - - - - -

(27)

NOW, ...

SHRINK THE BLACK HOLE
TO NOTHING

BUT STRINGS CAN STILL END
ON IT



COMPUTE THE MASS OF
"A POINT ON WHICH STRINGS
CAN END" VIA VACUUM POLARIZATION
AND GET $MASS \sim \frac{1}{g}$

(28)

SO THE NEW OBJECTS

ARE JUST

"POINTS (OR STRINGS
OR MEMBRANES) ON WHICH
STRINGS CAN END...."

CALLED "D-BRANES"

D-BRANES HAVE AN
AMAZING PROPERTY...

A SINGLE D-BRANE HAS A
POSITION WITH COMPONENTS

x^1, x^2, \dots, x^n BUT FOR

~~THESE~~ N IDENTICAL D-BRANES

THE POSITIONS BECOME $N \times N$
MATRICES WHOSE

EIGENVALUES ARE THE

POSITIONS IN THE USUAL SENSE

(30)

HENCE IN GENERAL ONE
CAN'T SIMULTANEOUSLY MEASURE
THE DIFFERENT COMPONENTS
OF POSITION OF D-BRANES

REMINISCENT OF

$$[p, x] = i\hbar$$

POSITION AND MOMENTUM

IN QUANTUM MECHANICS

A NEW ~~CONCEPT~~ ~~OF~~ KIND OF
NON COMMUTATIVITY IN PHYSICS.

(31)

APART FROM BUILDING UP
THE WEB OF DUALITIES, THIS
HAS BEEN CARRIED IN THREE
QUITE DIFFERENT DIRECTIONS

- ① UNDERSTAND BLACK HOLES
- ② UNDERSTAND FOUR-DIMENSIONAL
GAUGE THEORIES
- ③ LEARN WHAT THE THEORY IS.

① BLACK HOLES

CLASSICALLY, BLACK HOLES

ABSORB AND DON'T EMIT.

QUANTUM MECHANICS DOESN'T

ALLOW SUCH AN OBJECT

AND HAWKING DISCOVERED ~1975

THAT QUANTUM MECHANICALLY

BLACK HOLES EMIT APPROXIMATELY

THERMAL RADIATION AT

$$T \sim \frac{1}{G_N M}$$

$M = \text{MASS}$
 $G_N = \text{NEWTON}$
 CONST

THERMODYNAMICALLY,

(33)

A BLACK HOLE ACTUALLY

HAS AN ENTROPY

$$S = \frac{1}{4G_N} \cdot \text{AREA OF HORIZON}$$

USUALLY

$$S = \text{LOG (NUMBER OF QUANTUM STATES)}$$

BUT WHAT ARE THE QUANTUM STATES OF A BLACK HOLE?

WITHOUT A THEORY OF QUANTUM GRAVITY ONE CAN'T ANSWER AS ONE DOESN'T KNOW "WHAT ~~THE~~ BLACK HOLES ARE MADE OF"

WITH THE NEW UNDERSTANDING ⁽³⁴⁾
OF STRING THEORY, ONE KNOWS
WHAT BLACK HOLES ARE MADE
OF, AT LEAST IN CERTAIN
CASES.

FOR INSTANCE BY PUTTING
TOGETHER MANY IDENTICAL
D-BRANES TO OBEY

$$M \gg \frac{1}{g^2}$$

ONE CAN MAKE A
BLACK HOLE OF D-BRANES,
AND THE MICROSCOPIC
DESCRIPTION OF THIS BLACK
HOLE HAS A

$U(N)$ GAUGE SYMMETRY

FROM THE POSITION MATRICES
OF THE D BRANES.

SO IN THIS PARTICULAR
CASE, WE GET

A GAUGE THEORY MODEL OF BLACK HOLES

AND BY SOLVING THE
GAUGE THEORY ONE HAS
OBTAINED FOR THE FIRST
TIME

A MICROSCOPIC EXPLANATION OF BLACK HOLE ENTROPY

(VAFA, STRUWINGER, CALLAN, MALDACENA...)

② MANY OF THE MYSTERIES
OF FOUR-DIMENSIONAL^{QTM} GAUGE

THEORIES SEEM TO DEPEND

UPON MYSTERIOUS ELECTRIC-

MAGNETIC DUALITY SYMMETRIES

THAT EXCHANGE THE TWO

FAMILIAR KINDS OF

PARTICLES



ELEMENTARY
QUANTA

MASS ~ 1



SOLITONS

MASS $\sim \frac{1}{g^2}$

FOR INSTANCE, IT SEEMS
THAT "QUARK CONFINEMENT" IN
QCD HAS TO DO WITH
"CONDENSATION OF MONOPOLES"
AND IS THUS "DUAL" TO A
MORE ACCESSIBLE HIGGS
MECHANISM.

THIS IDEA GOES BACK TO
THE 1970's, BUT HAS
BECOME MUCH MORE CONCRETE
IN THE LAST FEW YEARS
AS SUPERSYMMETRY WAS BROUGHT
TO BEAR TO CONSTRUCT

A WEB OF DUALITIES AMONG ⁽³⁹⁾
FOUR-DIMENSIONAL FIELD THEORIES.

THIS WEB TURNS OUT TO BE
RELATED IN INNUMERABLE WAYS
TO THE STRINGY WEB OF DUALITIES



AND THE ~~RECENT~~ NEW
STRING THEORY METHODS HAVE
SHED A LOT OF LIGHT ON
THE FOUR-DIMENSIONAL
FIELD THEORIES....

(40)

ONE REASON FOR THIS IS
THAT THE D-BRANES
ACTUALLY MAKE ELECTRIC-
MAGNETIC SYMMETRY MANIFEST:

ORDINARY



$$M \sim 1$$

D-BRANE



$$M \sim \frac{1}{g}$$



SOLITONS



$$M \sim \frac{1}{g^2}$$



't HOOFT - POLYAKOV

③ FINALLY, THE MOST

FUNDAMENTAL QUESTION:

WHAT IS THIS MYSTERIOUS

M - THEORY THAT PHYSICISTS

HAVE STUDIED IN DIFFERENT

WAYS FOR MORE THAN

A GENERATION?

IT IS SURELY BASED ON

COMPLETELY NEW PHYSICAL

PRINCIPLES. WHAT ARE

THEY?

STRING THEORY HAS ITS
ROOTS IN THE FORTUITOUS
DISCOVERY IN 1968 OF A
FASCINATING FORMULA
"THE VENEZIANO AMPLITUDE"

WHICH IS ~~THE MOST FUNDAMENTAL~~
USEFUL ~~AND FUNDAMENTAL~~
BUT NEITHER THE MOST USEFUL
NOR MOST FUNDAMENTAL
FORMULA IN THE SUBJECT


(43)

WE'VE HAD NO CHOICE FOR
29 YEARS BUT TO HEAD
BACKWARDS AND TRY TO
FIND THE DEEPER IDEAS
AND STRUCTURES IT CAME
FROM

THIS HAS LED TO A LONG
TRAIL^{OF} DISCOVERIES, AND
SURPRISES

HIGHLIGHTS HAVE BEEN

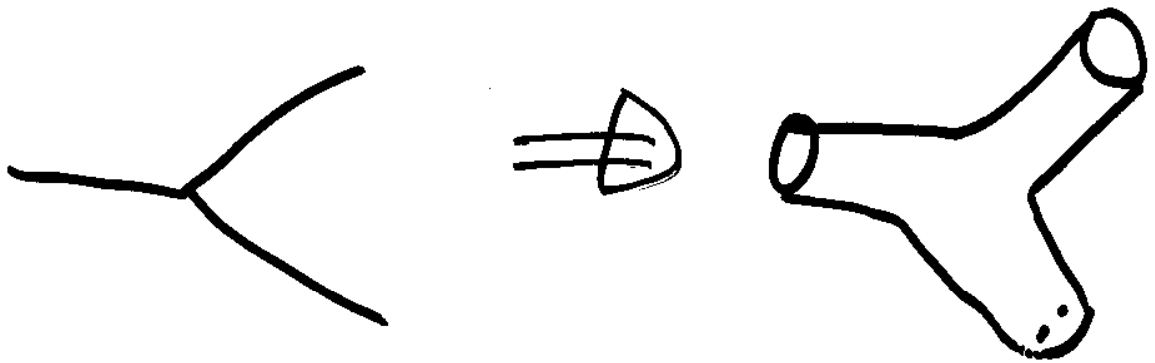
(44)

- * THE STRING PICTURE
- * THE INEVITABILITY OF QUANTUM GRAVITY
- * EMERGENCE OF THE CONCEPT OF SUPERSYMMETRY
- * ELIMINATION OF THE INFINITIES OF QUANTUM FIELD THEORY
- * ATTRACTIVE WAYS TO INCORPORATE THE STANDARD MODEL 
- * NEW INSIGHTS ABOUT THE NATURE OF SPACETIME
- * AND NOW, UNIFICATION OF THE SUPERTHEORIES IN "M-THEORY..."

BUT WHAT IS THE THEORY
BEHIND ALL THIS?

(45)

WE'VE LONG KNOWN THAT THERE
IS A NEW FUZZINESS, ROUGHLY
ANALOGOUS TO QUANTUM UNCERTAINTY,
AS EVEN AT $\hbar = 0$ THERE IS
NO NOTION OF A DEFINITE
SPACE-TIME EVENT



BUT HOW TO MAKE IT CONCRETE?

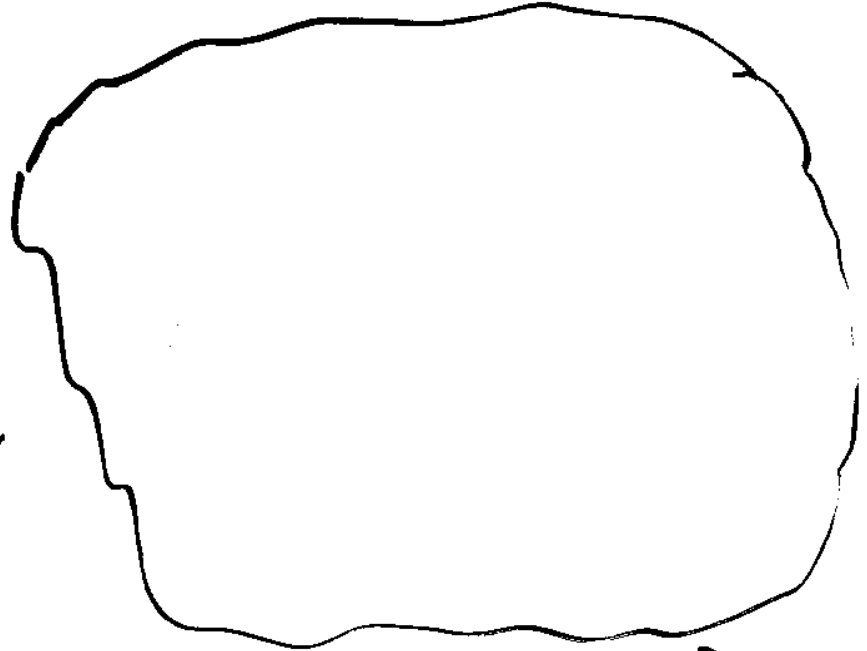
WHAT IS THE ANALOG OF

$$[p, x] = -i\hbar ?$$

NON COMMUTING D-BRANE POSITION
MATRICES SEEM TO BE A CLUE

WITH PARTIAL SUCCESS
THERE'S BEEN CONSTRUCTED A
"HOLOGRAPHIC MODEL" OF THE
UNIVERSE

IN WHICH
ALL
INFORMATION
IS STORED



AT SPATIAL INFINITY
IN THE FORM OF D-BRANE
MATRICES

(BANKS, FISCHLER,
SHENKER, SUSSKIND)

(47)

IT SEEMS CLEAR THAT THE
EVENTUAL UNDERSTANDING WILL
BE AT LEAST AS STRANGE
AND EXCITING AS THIS

...